Suction measurements on a natural unsaturated soil: a reappraisal of the filter paper method

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ABSTRACT: Soil suction measurements on an unsaturated soil were performed using the filter paper method and a high capacity tensiometer so as to analyse the reliability of the filter paper technique. The results show that an alternative approach of the filter paper method based on using a previously wetted filter paper can fruitfully be used to measure suction provided an appropriated calibration curve is used. This method was compared to the standard filter paper method in which the paper is initially dry and a good agreement was found between the two approaches, being the "wet" method somewhat faster in terms of suction equilibration. Suction data also agree well with results obtained independently using a home made high capacity tensiometer. The two methods finally provide a first outlook of the water retention properties of an unsaturated loess from Northern France, observing some evidences of hydraulic hysteresis on it.

1 INTRODUCTION

Soil suction measurements by the filter paper technique were compared with experimental data obtained by a high capacity tensiometer to analyse the reliability of the filter paper method and additionally to characterize some water retention properties of a natural unsaturated loess. An alternative approach of the filter paper method, proposed by Parcevaux (1980) and based on using a previously wetted filter paper, was experimentally tested to measure suction by utilizing an appropriated calibration curve. Results obtained by this approach were compared to data obtained by the standard filter paper method (ASTM, 2003, D 5298-03) in which the paper is initially dry.

Hysteresis effects in filter paper have been observed, taking into account that initial water content is different for both approaches. Experimental data obtained by different researchers (Fawcett & Collis-George, 1967, Parcevaux, 1980, Hamblin, 1981, Greacen et al., 1987, Ridley, 1995, Harrison & Blight, 1998, Leong et al., 2002) were presented showing the influence of filter paper hysteresis effects in soil suction measuring.

Suction equilibration time between filter paper and soil was also analysed for both filter paper approaches. In according with the ASTM procedure, a period of seven days is recommended for the dry filter paper approach whereas there are not enough experimental data for the wet filter paper approach. Because initial water content is different for both approaches, the equilibration time could be different in view of the possible differences in either wetting or drying processes.

This paper investigates the filter paper method by direct measurement of suction on a natural unsaturated loess from Northern France (Cui *et al.* 2004, Delage *et al.*, 2005, Yang *et al.*, 2009). Experimental results show a good agreement between both approaches of the filter paper method and also with the tensiometer measures. Shorter periods of suction equilibration were observed for the "wet" filter paper method.

2 MATERIAL AND EXPERIMENTAL METHODS

2.1 *Bapaume loess*

The soil used in the experiments is an intact and unsaturated loess extracted from a deposit located in an area near to the city of Bapaume (Northern France). These loess deposits were formed during the Quaternary period under periglacial conditions, concerning the aeolian transport of silt particles eroded by a constant North West wind (Antoine 2002, 2003). This soil is characterized by a relative homogeneity, a low plasticity, a high porosity, a weak carbonate bonding and an open structure that explains its susceptibility to collapse when saturated (Cui et al. 2004, Delage et al., 2005, Yang et al., 2009).

Exploration works were made by manual cutting in order to keep the natural structure of loess, considering its high fragility. Intact loess blocks were extracted in cubic boxes of 300 mm side and then protected by paraffin and plastic film to avoid evaporation. The void ratio at natural state is about 0.85, the natural water content is 14% and the initial degree of saturation is 44%. The sand, silt and clay fraction are equal to 2, 82 and 16% respectively. The dominant clay minerals are kaolinite, illite and interstratified illite-smectite (Karam 2006). The carbonate CaCO3 content is 6%. The plasticity index is quite low (Ip = 9, wp = 37%, wl = 28%) and the Casagrande classification of the loess is CL.

2.2 *The filter paper method*

The filter paper technique was standardized by the ASTM (2003, D 5298-03) to measure suction values ranging from 0.01 to 100 MPa. Filter paper measurements are performed by placing a piece of filter paper in contact with the soil sample so as to attain suction equilibrium between the filter paper and the sample. The suction value is derived from the calibrated water retention curve of the filter paper. In this work, Whatman No. 42 filter paper was employed. The initial water content under ambient laboratory conditions of the Whatman No. 42 filter paper in original boxes is around 6% (Marinho & Oliveira, 2006) that corresponds to a suction of 29 MPa, which is almost the upper limit for measuring suction.

An alternative method using initially wet filter papers was reported by Parcevaux (1980). This approach is here referred to as *wet filter paper method* compared to the ASTM *dry filter paper method*. When an initially dry paper is used as recommended by the ASTM procedure, the filter paper is submitted to a wetting path during suction equilibration. Suction measurements with the wet filter paper approach concern drying paths during suction equilibration from a wet state near to 150% of filter paper water content.

The tests were performed on samples of 70 mm diameter and 19 mm height. They were cut carefully to get a surface as planar as possible in order to ensure a good contact with the filter paper piece. A set of three filter paper pieces of 50 mm diameter was prepared and placed between two soil samples. The central piece was smaller to avoid pollution due to soil particles. The overall set was then covered with paraffin wax and enveloped in a plastic film to avoid evaporation during the equilibration time. The set was put in an insulated plastic box reducing temperature perturbations. After seven days of suction equilibration, the set was opened and both soil samples and the central piece of filter paper were weighed with a precision balance (1/10 000 g). Weighing was as quick as possible to avoid any evaporation. Finally, suction was calculated from the filter paper water content using the appropriate calibration curve depending upon the initial state of the filter paper.

Figure 1 presents the results of filter paper calibration curves made by different researchers (Fawcett & Collis-George, 1967; Parcevaux, 1980; Hamblin, 1981; Greacen et al., 1987; Ridley, 1995; Harrison & Blight, 1998; Leong et al., 2002) using either drying or wetting processes. Data below 1 MPa were calibrated by suction control techniques such as suction plate, pressure membrane extractor, psychrometer and Richard's apparatus whereas higher suctions were controlled with vapour equilibrium technique using saline solutions.

The calibration curve of the wet filter paper method was obtained from drying paths and that of the dry filter paper method from wetting paths. These paths correspond to the water transfer processes occurring within the filter paper during the paper/soil equilibration periods, concerning water extraction from the soil in the dry method and water adding from the filter paper to the soil in the wet method.

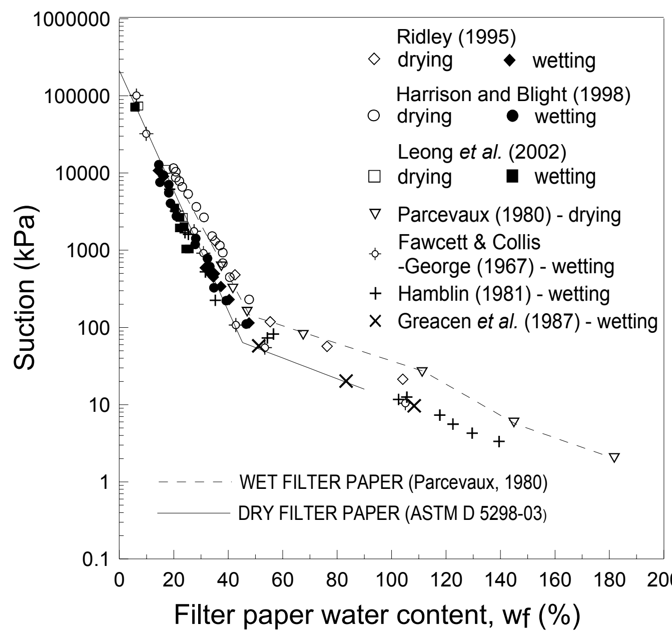

Figure 1. Whatman No. 42 filter paper calibration curves

A good agreement is observed in Figure 1 between data obtained independently with different suction control techniques by different authors at different times. The data describe a space between both wetting and drying curves that concerns the hysteresis of the water retention curve of the Whatman No. 42 filter paper. The phenomena of hysteresis in the filter paper have not influence in the soil suction measurement if the correct calibration curve is used for each approach.

2.3 *High capacity tensiometer*

In order to compare filter paper suction measurements, another suction measurement technique was used. It consists on a high capacity tensiometer developed in the CERMES laboratory, inspired on the original idea of Ridley and Burland (1995) and previously detailed in Mantho (2005) and Cui et al. (2008). The CERMES HCT (high capacity tensiometer), detailed in Figure 2, is an integral strain gauge tensiometer (Tarantino 2004, Delage et al. 2008) composed of a porous high air entry value (1.5 MPa) ceramic disk with strain gauges glued to a metallic diaphragm and a water reservoir of 0.1 mm thickness.

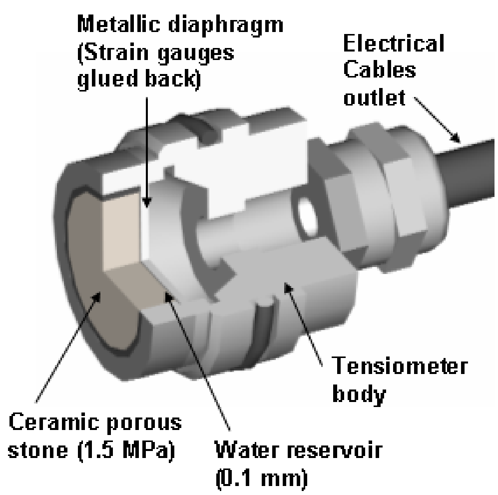

Figure 2. Peeling off of high capacity tensiometer (HCT CERMES)

This sensor is characterized by a range of suction measurement from 0 to about 800 kPa. As proposed by Tarantino and Mongiovi (2001), a process of saturation was conducted by the application of 4 MPa of positive water pressure to get rid of any air trapped in the system. Then, the HCT was submitted to a process of cavitation by putting it in contact with a dry sample and then resubmitted to a 2 MPa positive water pressure. As suggested by Mantho (2005), cycles of cavitation – saturation are highly recommended to improve the tensiometer functioning.

Suction measuring was performed by using a modified oedometer cell that had been already utilized to perform oedometer testing, measuring the suction evolution (Delage et al. 2007, Tarantino and De Col 2008). The HCT was inserted into the base of the modified cell. A soil sample of 70 mm diameter and 19 mm height was inserted in a metallic ring and placed over the oedometer base. The set was then placed over a precision balance to register the soil weight changes. A fine layer of loess slurry was placed on the tensiometer's surface to avoid the early cavitation of the HCT and to improve the contact between it and the soil specimen. A piston applying 1.5 kPa of vertical pressure was placed over the soil sample to the same reasons.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 *Wetting and drying processes*

For both suction measurement methods, hydraulic paths were started from the loess natural water content (14.2%), and followed by either drying or wetting stages. Drying was performed by allowing evaporation of the soil specimen under laboratory conditions for periods of time comprised between 1 and 4 hours. Wetting was attained by adding small quantities of water to the soil sample. In this case, a piece of filter paper was placed on top of the sample and water drops were uniformly distributed over the surface using a syringe in order to ensure homogeneous wetting. Once the target water content was obtained, a new suction measurement was taken.

3.2 *Equilibration time for the filter paper method*

Suction measurements on loess samples were performed by using both the dry and wet filter paper methods to compare obtained values and required equilibration times. Testing periods of time varied from 1 to 12 days. Tests were carried out with four samples at the following initial water contents: 23.8, 13.33, 7.88 and 7.19%, corresponding to suction levels about to 13, 46, 144 and 350 kPa respectively.

Figure 3 presents the time evolutions of suction for all tests. Each point corresponds to a measurement of the water content of the filter paper at a given time (between 1 and 12 days) after the contact between the filter paper and the soil has been ensured. After each weight measurement, a new filter paper was put in contact with the soil sample and a longer equilibration time was allowed before performing a new measurement.

Suction variations with time, related with filter paper water content, are the consequence of water transfers between the soil and the filter paper. For the dry method (resp. wet method), it is observed that the filter paper extracts water from the soil (resp. releases water to the soil). Water transfers tend to stabilize after a few days, generally before the seven days period mentioned in the ASTM recommendation.

Monotonic changes in suction are observed at 13.33% and 7.88% whereas some oscillations are observed at 23.8% and 7.19%. In the driest samples (w = 7.88% and 7.19%), a significant drying of the initially wet filter paper occurs very quickly with relative changes higher than 0.15g of water mass occurring during the first day. Not substantial reasons were found for these oscillations, especially at the water content level of 7.19% corresponding to 350 kPa of suction around.

However, a good agreement in terms of final suction is observed at the end of all the tests with slightly higher values given by the dry filter paper method. This good agreement is also observed in the case where oscillations are observed. In wet samples, the difference appears to be smaller than 1 kPa for suction values of 12.6 (w = 23.8%) and 46.8 kPa (w = 13.33%). The highest difference is observed at 7.19% (44.6 kPa with the wet paper and 111.5 kPa for the dry one).

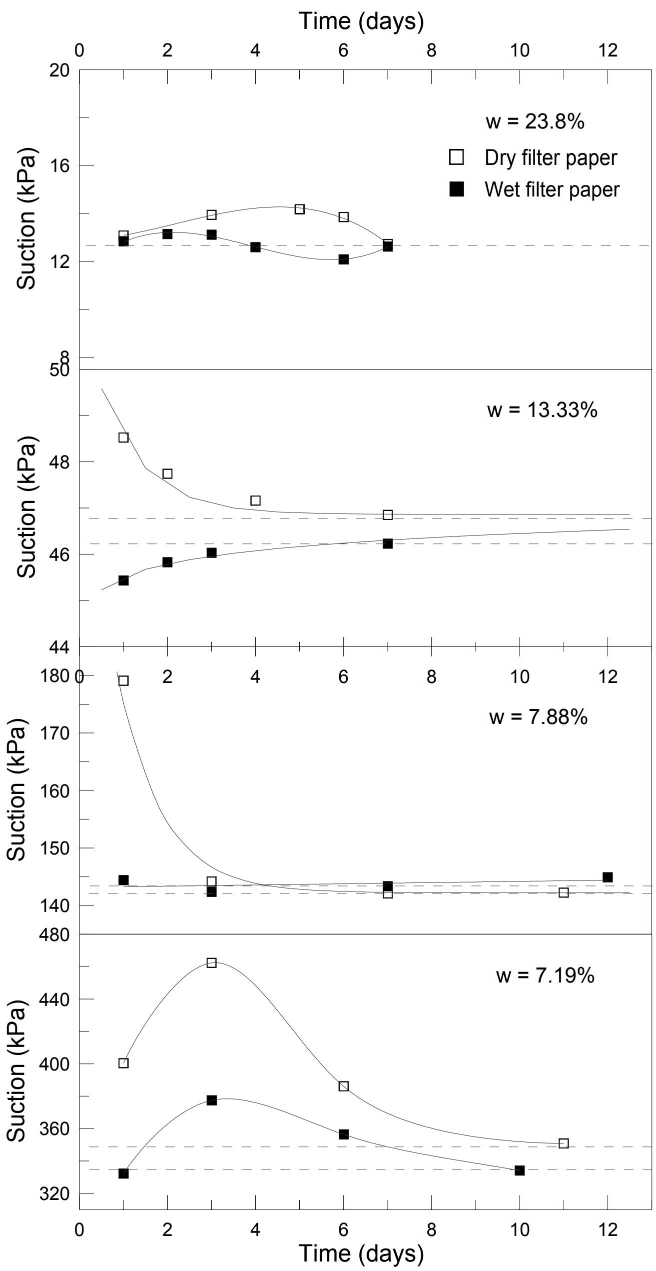

Figure 3. Time evolution of suction measured with filter paper techniques

It is observed a good agreement between the two protocols for the filter paper method with the minor influence of the presence itself of the filter paper on the measured suction. In Table 1, equilibrated values of water exchange ratio between filter paper and soil are presented for each initial water contents and for each method at all final measurement stages. This rate corresponds to the variation of the mass of water in the filter paper during the measurement (ΔM_w^{FP}) divided by the total mass of water present in the soil sample (M_w^{soil}). The low observed values confirm that the filter paper technique is a reliable technique of measuring suction and that both protocols provide comparable results in terms of measured suction.

Table 1. Ratio of water exchange between filter paper and soil

w_i*	WFP*	DFP*
(%)	(‰)*	(‰)*
23.80	0.74	2.04
13.33	2.86	1.93
7.88	9.89	2.58
7.19	10.02	2.15

w_i*: Initial water content
WFP*: Wet filter paper
DFP*: Dry filter paper
(‰)* : Water exchange ratio (per thousands)

From the point of view of equilibration time and variability of measures, it appears (see Figure 3) that the wet filter paper method gives less variable measures than the dry filter paper method. The wet filter paper method also seems to provide a quantitatively shorter measure of suction time as compared to the dry filter paper method. In almost all cases, measurements confirm the 7 days equilibration time standardized by ASTM.

3.3 *Suction measurements*

Suction measurements were carried out by the HCT and the wet and the dry filter paper methods to compare the obtained experimental results. Hydric paths, consisting on either drying or wetting processes, were started from the natural loess water content of 14.2% that corresponds to an initial degree of saturation of 44% and a suction of 40 kPa as measured by the filter paper (wet or dry) and the HCT.

After each change in water content in the HCT hydric paths, an equilibration time of 1 hour was waited for before measuring suction with the HCT. Experimental observations showed 4 to 10 min of HTC response time in wetting stages, and 45 min to 1 hour in drying stages.

Various hydraulic paths corresponding to wetting and drying processes into the suction – water content space were performed. Three wetting hydraulic paths starting from the natural state were made at low suction values (Figure 4). Other three hydraulic paths starting by drying were performed at high suction values (Figure 5).

Paths in Figure 4 were firstly conducted by wetting process followed by drying (paths 1, 2 and 3). Paths in Figure 5 started by drying followed by some wetting steps (paths 4, 5 and 6). Observed hydraulic paths show that suction increases currently when water content decreases, and conversely.

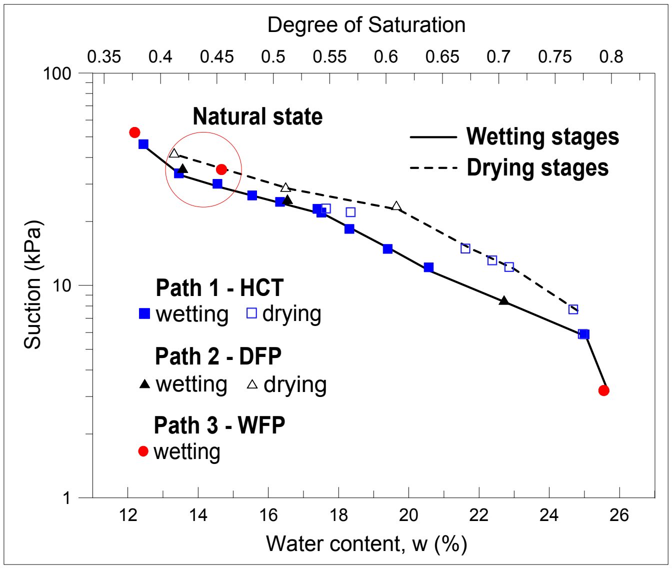

Figure 4. Hydraulic paths wetter than natural state

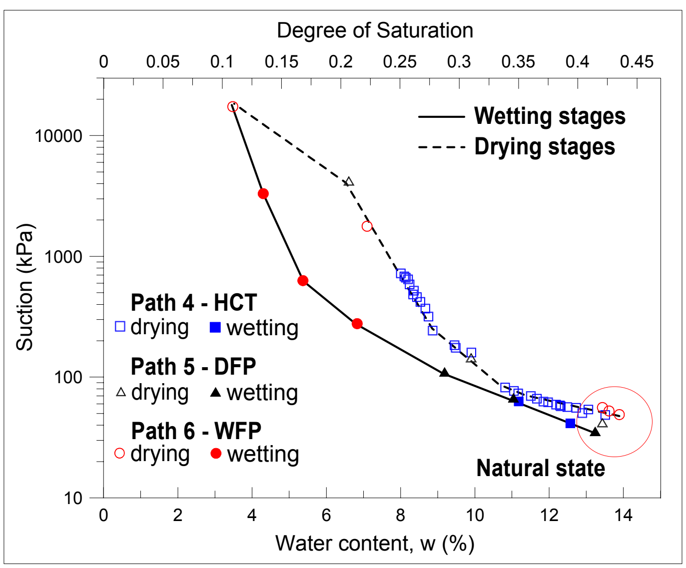

Figure 5. Hydraulic paths drier than natural state

A good agreement is observed between results obtained by the techniques used. Wetting and drying data obtained from HCT measurements show relatively smooth evolutions of suction with respect to water content.

CONCLUSIONS

Two approaches of the filter paper method were identified in this work. The first one was the standardized technique by ASTM (2003, D 5298-03) consisted on putting a dry filter paper piece in contact with a soil specimen. Suction values were obtained by measuring the filter paper water content at final stage of the equilibration time between filter paper and soil, which was seven days as recommended by ASTM. The second one was proposed by Parcevaux (1980) consisting on using an initially wetted filter paper piece instead of a dry one. The calibration curves for both methods, giving soil suction from filter paper water content, were presented following the analysis made by Leong et al. (2002). Hysteresis phenomena in filter paper were also identified.

The suction equilibration time by both protocols of the filter paper technique was also investigated. Shorter equilibration periods were observed for the wet filter paper approach. Measures confirmed the seven days equilibration time proposed by ASTM.

Suction measurements on a natural unsaturated loess were performed by both protocols of filter paper, having experimental data obtained by the CERMES high capacity tensiometer as a reference. Experimental data obtained by both filter paper approaches match well with the HTC measurements. From Figures 4 and 5, it can be seen that drying and wetting branches are not parallels, but apparently converge towards a point corresponding to the natural state (w = 14%, s = 40 kPa). The gap existing between them is better known as hydraulic hysteresis, and it is more remarkable at higher levels of suction (s > 100 kPa).

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